FRICTIONAL IGNITION OF GAS BY MINING MACHINES

BY IRVING HARTMANN

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Irving Hartmann 1/

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INTRODUCTION

Several recent ignitions of firedamp - a mixture of methane and air - in American coal mines have been attributed to frictional heating when hard rocks were struck while cutting and drilling coal seams. Although none of these ignitions caused severe explosions, they call attention to a problem that can become increasingly significant as mechanized mining is developed further. The power in and rapid release of energy from high-speed machinery has increased the rates of advance into virgin coal creating many problems. Unforeseen faults and hard mineral inclusions may be encountered; coal brought down in this way is finer in size; more gas is released from the seam; it is frequently more difficult to provide adequate ventilation at the face; and new roof-support problems must be solved. In particular, continuous mining machines (also known as continuous miners) greatly increase the frequency of contact between cutter bits and minerals. In view of these conditions, it may be expected that more gas ignitions will occur as a result of frictional heating unless the situation is understood and remedial measures are introduced.

The problem of frictional heating is not new in coal mining. In Europe, particularly in England, it has been a concern for more than a century. During the last 15 to 20 years frictional ignitions have been a major cuase of explosions in British mines. Explanations for the greater number of such ignitions in England may be the special character of the coal measure strata, the mining methods, the rate of gas emission and possibly its composition, and less effective ventilation near the face. To reduce the ignition hazard, considerable laboratory and field research has been conducted, particularly by the Safety in Mines Research Establishment, Ministry of Fuel and Power of Great Britain. Much of the information presented in this report has been drawn from these studies.

The purpose of this paper is to call the attention of mine operators to potential ignition hazards associated with the use of mining machines; correct certain misimpressions regarding the relative effects of various metals in cutting bits and other equipment; review several ignitions and explosions caused by friction; summarize findings of research on the subject; outline the possible mechanisms of ignitions; and discuss preventive measures against explosions. Although the report is concerned primarily with ignitions by mining machines, some consideration is given to related ignitions by friction and impact between rocks, by contact of metals with rocks or with other metals while setting and withdrawing roof supports,

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etc. Ignition by friction in industrial plants, where the problem long has been recognized, is discussed briefly.

Although considerable basic knowledge has been obtained on the origin and cause of frictional ignitions and various preventive measures have been developed, much is still unknown and the present safeguards are not perfect. Research now in progress should contribute valuable information on ignition by friction in gassy mines and means of prevention.

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NATURE OF FRICTIONAL HEATING AND IGNITION

Heat is produced whenever energy is utilized to perform work or when one form of energy is converted to another form, for example, when electrical energy is converted to mechanical energy in electric motors. In general much heat is evolved by the friction and impact of objects. The release of heat under most conditions raises the temperature of adjoining objects and the surrounding atmosphere. When the amount and rate of heat production is high and occurs within a small space, the temperature increase may be considerable. Friction and impact can cause heating of one or both contacting surfaces to a faint or even an intense glow, smoldering, smoke, sparks, flashes, flame, and what appear to be electrical discharges. In the presence of combustible vapors, gases or dusts, the heat produced by friction may be a potent source of ignition.

In mining coal, large forces are applied and much energy is expended. Many machines depend on friction for their effectiveness, and various materials, including rocks and metals, come into frictional and impact contact, frequently in the presence of an explosive atmosphere. Accordingly, the problem of heating and the possibility of ignitions must be considered in the design, construction, and use of mining machines. To produce an ignition the amount of mechanical energy converted to heat need not be large, but heat must be liberated rapidly and within a small volume. The nature of the contacting surfaces, the type of contact, and the composition and ignition temperature of the combustible atmosphere are also important factors, which will be discussed later in some detail.

In general, flammable mixtures of gas are ignited by frictional heating in two ways: (1) A small volume of gas is heated to the ignition temperature by direct contact with a hot part of one of the rubbing surfaces; (2) small heated particles, commonly termed frictional sparks, are projected into the gas mixture. These frictional sparks are small, hot particles of solid matter torn from one of the larger pieces in contact. The particles may be inert, in which case their temperature is limited by their melting point, or they may be chemically active, in which case their temperature is augmented by oxidation. The existence of frictional sparks should be considered as a warning in coal mines where a flammable atmosphere exists, but they do not necessarily mean that an ignition or explosion will occur. To ignite the gas, the sparks must have a high temperature and their heat content must be sufficient to impart the necessary amount of heat to a small volume of the

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gas mixture. The ability of sparks to ignite firedamp is greatly restricted by the short period of contact with the gas, owing to cooling by convection, and to the "ignition lag" period of the gas, which varies with composition and with temperature. All these factors make flying sparks generally less dangerous than sparks whose paths are obstructed by a thermal insulator at an early stage.

FRICTIONAL IGNITIONS IN INDUSTRY

The sensitivity of many gases, vapors, dusts, pyrotechnic mixtures, explosives, and other compounds to ignition by hot surfaces and by sparks produced by friction and impact is very important in many industries. Many fires and explosions have been attributed to these causes and considerable attention has been given to alleviating the hazard. Excessive heat or sparks can be produced by neglected or worn bearings of rotating machines; during grinding, machining, buffing, and other finishing of metal objects; during repair and construction work; in using various hand tools; by friction or breaking of fan blades; through entry of tramp iron into pulverizing mills; by picks, shovels, and similar implements striking concrete floors; by friction of slipping machine belts; and in many other ways. In industry the majority of frictional ignitions are caused by metal-to-metal contacts, whereas in coal mines such accidents have been due primarily to metal-rock friction, as with cutting machines. Ignitions and explosions have been observed as a result of frictional heating in plants producing gasoline, naphtha, and other vapors; primary explosives; sulfur, plastics, grain, flour, and many other dusts.

Industrial safeguards against frictional ignition include proper maintenance of machines to avoid overheated bearings; segregation of spark-producing operations from other plant areas; adequate ventilation and suitable dust-collecting systems; magnetic separators to prevent entry of ferrous metal into machines; substitution of inert gas for air in closed equipment; prohibition of shoes with exposed cleats or nails; substitution of spark-resistant tools for ordinary steel tools; etc.

Spark-resistant tools, frequently termed "nonsparking" tools, are used in various industries where explosion hazards exist. Safety codes of the National Fire Protection Association recommend this practice under certain conditions. In Western Germany, iron or steel tools are prohibited in places where volatile substances are stored or where explosive gases, vapors, or dust are present in dangerous quantities. Ideas regarding the effectiveness of spark-resistant tools have undergone considerable change. At one time it was believed that elimination of steel and iron tools would do away with frictional ignition hazards. Later it was found that other materials, including light alloys, especially those containing magnesium, can produce highly incendive sparks by contact with other metals or with concrete. The most commonly used spark-resistant tools are made of various copper alloys, with beryllium-bronze the preferred material. Beryllium alloys are suitable because by proper heat- and solution-treatment they can be hardened and provided with cutting edges and other desired characteristics. It is realized now that even spark-resistant tools can produce incendive sparks under some conditions, for example, if the impact energy is great enough to break or tear off small parts of the metal that is being worked and heat these fragments to a high temperature or induce their rapid oxidation. Various tools for handling hazardous materials are made of wood, leather, and plastics.

The friction of ferrous metals produces much sparking, owing to the ease with which iron oxide is formed in air when iron particles are detached from larger pieces. The particles are first preheated by the energy required to tear them from the parent metal; this is followed by rapid exothermic oxidation, which raises

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their temperature to incandescence. The copper used in spark-resistant tools has a much lower heat of combustion than iron. In addition, the heat capacity of copper is higher, resulting in much lower temperatures than with iron and little or no sparking in most instances.

MINING OPERATIONS CAUSING FRICTIONAL IGNITIONS

In many mining operations the heat produced by friction and impact is high enough to ignite firedamp or coal dust under certain conditions. In Great Britain where most firedamp ignitions of this nature have been reported, the great majority occurred while cutting coal seams with machines; this was also an important cause of ignitions in other countries. Other causes of frictional ignitions were drilling in the seam; hand picks used for testing the soundness of roof strata, breaking rocks, and testing and cleaning faults; hand shovels striking roof rocks; sledge hammers and other tools striking rocks; continuous miners cutting hard rock inclusions in coal seams; sliding and impact of rocks on other rocks during roof falls and roof caving; steel chocks and props being forced during withdrawal of roof supports; derailing and wreckage of runaway trips of mine cars; projection of detonator fragments from shot holes during blasting; fan blades rubbing against fan casings; and operation of conveyor belts and belt slippage. Heat and sometimes strong sparks have been observed when rock is projected by pneumatic stowers and while loading mine cars, sliding metal roof props in chutes, and tightening roof bolts.

The surfaces whose friction or impact has resulted in dangerous heating or sparking include rocks against rocks, metals (especially steel) against rocks, steel against steel, light metals against steel. The mine rock most likely to create a hazard is siliceous or quartz-bearing sandstone, with iron pyrite next. A few ignitions have been reported when hard shales and ironstone (a stratified iron ore, generally siderite) were struck by steel.

HISTORY OF GAS IGNITIONS BY FRICTION IN COAL MINES

Great Britain

Observations of streams of sparks, lightning-like flashes, and great noise accompanying friction and impact of sandstone rocks during caving and collapse of roof strata date back to 1886. The first firedamp explosion attributed to frictional heating between rocks was reported at the Maindy pit, Glamorgan, Wales, in 1896. It was caused by a fall of roof, which was composed almost entirely of quartz with small inclusions of iron pyrite. When pieces of the rock were subjected to the friction of one piece rotating at 200 r.p.m., firedamp was readily ignited. Three explosions at the Bellevue mine, Alberta, Canada, during the first decade of this century were attributed to falls of rock consisting of bituminous sandstone of fine, even texture, with about 50 percent quartz and 16 percent carbonaceous matter. This rock was found to ignite firedamp during friction tests.

The possibility of igniting firedamp by contact of steel with rock was considered following a mine explosion at the Wallsend colliery, England, in 1785, which was thought to have been initiated by a Spedding mill -- a device that was used for illumination in mines before the introduction of the flame safety lamp. It consists of a rapidly rotating, thin disk of steel and a piece of flint pressed against the edge, producing a stream of sparks. In tests the device was found to be capable of igniting illuminating gas, but it was never proved that it could ignite firedamp.

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Early explosions in English coal mines attributed to frictional heating between metal and rock occurred at the Pentre colliery, Glamorgan, in 1880, when a pick struck hard rock; at Great Fenton colliery in 1883, owing to the same cause; and at Orrel colliery in 1902, when a shovel struck roof rock. In 1914 gas was ignited when a pick hit sandstone during roof brushing. Between 1920 and 1929, three explosions were started by frictional heat while operating coal-cutting machines. Between 1937 and 1952, 100 ignitions of firedamp in British coal mines were attributed to frictional heat while using cutting machines; 17 other ignitions were attributed to frictional heating resulting from drilling, striking rocks with hammers, using picks, and derailed mine cars. During the same period, 104 gas ignitions were caused by shot firing, 241 ignitions by open lights, 79 by electricity, and 82 by smoking. These sources account for 85 percent of all firedamp ignitions and explosions.

One firedamp explosion in 1950 was attributed to sparks produced when a drilling machine with a light alloy casing struck a steel roof support. Since then two other explosions were caused by sparks produced when rusty steel wedges were knocked out of light-alloy roof bars under load.

A very severe explosion owing to friction occurred at the Holditch colliery in 1937 when the picks of a cutting machine struck pyrite and ignited gas. Following an initial fire, 8 explosions occurred over a period of 4 hours, killing 30 people, most of them in the last explosion. The most serious explosion owing to frictional heating occurred at the Easington colliery in 1951, when a cutting machine struck pyritic inclusions in the shale bottom of the seam. The resulting gas ignition initiated an explosion of coal dust killing 81 men atmost instantly.

Germany

Since 1922 less than 10 coal mine explosions in West Germany have been attributed definitely to frictional heating. One firedamp explosion (1922) was started by a spark when a steel gear was struck with a chisel during repairs in a hoisting shaft. A second explosion (1922) was produced by the impact of a large piece of sandstone on a steel roof-support arch. A gas explosion (1923) was initiated when a steel roof support was struck with a tool. A strong gas explosion (1925) was attributed to sparks caused by a loose iron fan blade touching a damaged iron casing; as a result of experiments following this explosion, iron or steel fan wheels were prohibited and were replaced by wheels of a special light-metal alloy. Gas was ignited (1931) when a cutting machine struck pyritic inclusions in a coal seam.

In one mine gas was ignited (1933) while cutting a hard coal seam that contained neither pyrite nor sandstone inclusions. The compressed-air driven machine was greatly overloaded, and it stuck several times while the 360-foot long face was being cut. The setting of the cutter bits differed from the normal setting and produced much fine coal dust, requiring expenditure of much energy. After the accident part of the cutter bar was found about 4 feet from the machine to be broken and the cutter chain was bent; the condition of the bits indicated that they had been subjected to very high temperatures. During subsequent tests it was found that the methane in the cut ranged from 5.6 to 53 percent at various stages of the cutting cycle. It was concluded that the bits had been overheated by considerable friction, resulting in the ignition of fine coal dust, which in turn ignited the gas.

In 1953 gas was ignited when a pick struck a piece of rock in the coal bed. In January 1955 gas was ignited when a light metal mine-roof support was struck with a hammer.

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United States

In coal mines in this country frictional sparking, and ignitions of small volumes of gas have been observed on numerous occasions while cutting and drilling seams, while tightening roof bolts, and during other mining operations. These ignitions generally have not been considered important enough to form the subject of published reports. During the past 2 years the Bureau of Mines investigated 7 ignitions of this character. A brief account of these incidents follows.

In April 1953 at one mine 2 men were burned, when the cutting bits of a continuous miner contacted the sandstone roof, igniting methane from a feeder in the face of a crosscut. This machine applies a slow boring action to the coal face through two horizontal rows of rotating arms, which are staggered to cut intersecting circles in vertical planes, operating in a manner similar to a group of large core drills. When the machine first attacks a coal face the air can be made to circulate around the bits; however, as the machine head advances into the coal it occupies nearly the entire cross section of the bore, so that air flow is obstructed. About an hour before the ignition, the machine had advanced approximately 90 feet into the dead-end face of the entry. On examining the place an estimated 1.5 percent gas was found near the face. The machine was moved back 35 feet to drive a crosscut to an adjoining worked-out room after the gas had been removed. The crosscut was begun after a deflecting curtain was erected to within 3 to 4 feet of the rib immediately inby the machine to carry air to the machine. The crosscut was 9-1/2 feet wide -- the width of the machine -- and had been driven to a depth of 20 feet when the machine was stopped to permit change of shuttle cars. Normally this takes 3 to 5 minutes, and a test for gas is made during this time. However, on this occasion no test was made. Soon after the cutter head was started again gas was ignited. Ventilation in the cut was not adequate.

In January 1954 gas was ignited by a shortwall cutting machine when the bits struck hard sandstone in an undercut. The machine had just completed a cut 12 feet wide and 8 feet deep when it was stopped to make a test for gas. No gas was detected and cutting had been resumed when the ignition occurred. No one was injured, and the flame was quickly extinguished with rock dust. Ventilation was normal, with about 4,000 cubic feet per minute of air passing the face.

In May 1954, 2 gas explosions were initiated at a mine 2 days apart when bits of continuous mining machines encountered pyritic inclusions in the band of rock immediately above the coal bed. The machines were similar to the one mentioned previously. Four men were burned in the first explosion and one man in the second. The practice in this mine was to advance the machine about 25 feet into solid coal, then to pull back and widen the entry to desired size. The coal seam is gassy, and the manner in which the machine was designed and used, coupled with faulty installation of the brattice cloth, prevented adequate ventilation of the cut. Water sprays were being employed in this machine to allay the dust. Following these explosions a study was made to determine what changes in mining practice are advisable to prevent similar ignitions. It was recommended that advance of the machine into the solid should not exceed 8 feet, unless ventilation at the immediate face can be greatly improved. Further it was recommended that the end of the line brattice be kept close to the face; that doors, check curtains, and other ventilation facilities should be properly installed and maintained; and that mining operations be discontinued and power cut off from face equipment when the methane confent of the air near the machine exceeds 1 percent. Several of these measures were adopted, and during the past year no further ignitions occurred at the mine. The Bureau investigator also suggested that with continuous mining machines,

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normal mine ventilation should not be depended upon solely. Auxiliary mechanical means should be provided to supply an ample volume of air discharged at high velocity from one or more openings through the head of the machine against the face.

In July 1954 gas was ignited while completing a shear cut when the chain bits of the machine encountered pyritic lenses in the floor; the inby end of the shear cut was found to have penetrated about 8 inches into the bottom. Gas was thought to have entered the cut from a fault that was uncovered after the coal was removed. Cutting into the fault had been expected and gas in abnormal quantities was encountered in the adjoining entries while driving into the fault zone. However, no tests for gas were made before starting the shear cut in question.

In January 1955 an ignition of gas occurred shortly after beginning to drill a hole in drawslate above the coal seam at a place where a shelter hole was to be prepared. The ignition was attributed to friction of the drill bits with the rock. Neither pyrites nor quartz-bearing sandstone were reported in the drawslate. The drill was equipped with a water spray, but it is not certain whether this was in use. Shortly before drilling into the slate, the seam had been undercut and a hole drilled into the coal 8 inches below the drawslate. A test made for gas just before drilling began in the drawslate gave negative results.

In March 1955 gas was ignited while completing a shear cut when the cutting bits of the machine encountered a streak of iron pyrites "or some other hard material" near the floor. Water was being sprayed on the cutter bar to allay dust, and the ventilation at the face was said to be quite adequate at the time of ignition. The report of this incident indicates that the cutting bits had carbide tips. Similarly, the report of the previous ignition while drilling drawslate calls attention to the fact that tungsten carbide bits were used in the high-speed drills. These reports and oral accounts of observed sparking in other mines indicate that hardness of the contacting metal is important. In high-speed machine operations this may be a factor in frictional ignitions, although it is contrary to findings in British and German experiments.

EXPERIMENTAL WORK ON FRICTIONAL IGNITIONS

More than 35 years ago limited experiments were conducted by the Bureau of Mines to determine whether sparks produced when braking locomotive wheels would ignite explosive gas mixtures; no ignitions were obtained in these tests. In another early study on the ignition of gas by heated surfaces, it was found that the ignition temperature of natural gas was reduced by 300° C. when a layer of finely divided iron pyrite was placed on the metal bar being heated in the gas. After many trials it was found that a stream of natural gas could be ignited by directing it on a mass of pyrite dust that had been ignited by a frictional spark. More recently some experiments were conducted by the Bureau on ignition of dust clouds by frictional sparks formed by holding steel against an emery wheel. Dust clouds of aluminum, magnesium, titanium, and sulfur were readily ignited.

In Belgium many tests were conducted in an attempt to ignite firedamp by frictional sparks produced by contact of picks with rock surfaces. The results were negative in all cases. Ignitions were obtained by directing the picks in such a way as to produce glancing blows without sparks but with considerable heat at the points of contact. In other experiments it was found that under some circumstances a fan rotor and a casing made of an aluminum-base alloy produced fine dust that ignited firedamp by contact with a spark from iron.

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At the laboratories of the Netherlands State Mines it was found that a quick-release mechanism for roof supports, creating friction between steel and aluminum surfaces, can ignite firedamp. Ignitions could not be obtained when the aluminum was replaced by steel or when there was no rust on the steel friction surfaces. It was also impossible to produce ignitions with friction surfaces made of zinc or a light alloy free of silicon.

Firedamp was ignited in French experiments in 1928 by impact of steel picks against granite under very special conditions. In other experiments in the same year a few ignitions were obtained by sparks formed when steel was pressed against a carborundum wheel.

In 1886 an Austrian investigator succeeded in igniting firedamp by directing it against the point of contact between pieces of rock or iron and a sandstone mill-wheel. With rock against rock ignitions were obtained regularly, but in friction of iron against the sandstone only one ignition occurred.

Germany

In experiments conducted in Germany in 1922 no gas ignitions could be produced by impact of steel drill bits against steel plates. However, glowing particles of iron did produce ignitions if they burned. In 1931, during experiments with a cutting machine in quartz-bearing sandstone, it was found that strong sparks initially failed to ignite firedamp; soon afterward, however, brightly glowing strips appeared in the sandstone in the groove behind the cutting bits. Inspection of the sandstone block after each experiment showed that these grooves were covered with glowing steel particles from the bits, which adhered to the rocks as a result of the high frictional heat. In subsequent cutting these steel particles were heated still more, so that they flamed and ignited firedamp. After the experiments the bits showed considerable wear and scaly deposits. Firedamp was ignited with all types of bits.

Following a strong mine explosion in 1925 it was established that aluminum detonators ignite firedamp easily, as the aluminum is ejected in fine, burning splinters. As a result of this finding, for the first time light metal components were considered as a possible incendiary spark source. Tests in the German experimental mine showed that iron filings blown from a shot hole with permissible explosives produced bright and extensive showers of sparks without igniting firedamp. However, when a few aluminum shavings were added regular ignitions of firedamp occurred.

Since 1947 extensive experiments have been conducted to study the frictional ignition hazard of various steels and light alloys. Some of the resulting conclusions are given: Frictional sparks produced when steel props are compressed or released under pressure as a rule can cause a firedamp explosion under practical conditions; if steel props with aluminum alloy friction plates are used, reactions similar to the thermit reaction may occur under certain conditions and ignite firedamp; components of hard aluminum, containing silicon, may produce dangerous sparks during friction or impact with iron, but use of aluminum alloys with little silicon and considerable copper greatly reduces the ignition hazard; no incendive sparks were produced by friction or impact between aluminum alloys; sparks produced by friction or impact of steel on steel may ignite firedamp, particularly if the steel is covered with rust. In this connection it was found that sparks produced by the impact of rusty iron on aluminum only ignited firedamp immediately at the point of impact, whereas sparks caused by striking steel with rusty iron are

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incendive about 10-20 cm. from the point of impact. It is suggested that the danger might be reduced by coating the steel, as with zinc chromate, to prevent immediate contact between steel or rust and the other metal. The possible usefulness of a coating on light metal components is also mentioned.

Great Britain

Systematic research on the causes of frictional ignitions in coal mines was begun in England more than 30 years ago. Much progress has been made, and the work is continuing. Investigations have included fundamental studies on the mechanism of ignition, experimental studies in laboratories, and tests in coal mines to develop preventive measures against ignition. Laboratory experiments have dealt with the production and effects of frictional heat and sparks between rocks, steel, and light metals; sliding friction, direct impact and frictional impact between surfaces; stationary and flying sparks; sparks produced by picks, shovels, and other hand tools and by cutting machines; the effects of gas composition and oxygen content of the atmosphere; the role of speed of contact or energy release and of other parameters. Tests were made with falling weights against targets; high-speed impact of metal spheres against objects; pendulum-type friction devices; rotating wheels; electrically heated particles of metals in gases; and under other conditions.

Some of the earliest experiments studied the ignition of firedamp by the heat of impact of rocks. When the edge of a block of sandstone was placed against a revolving wheel of the same material, it was found that ignitions could be obtained easily and that weak mixtures of methane and air were easier to ignite than rich mixtures. Comparatively small energy was needed for the ignition, which was not produced by sparks but by a heated area on the rock surface at the point of contact. Some tests showed that firedamp can be ignited by hot particles thrown off by the abrasion of sandstone rocks, but such ignitions were only obtained when the heat was sufficient to fuse the stationary rock and a heated area on its surface, which was itself capable of igniting the gas. No sharp distinction could be made between the different sandstone rocks tested, but the quartzitic types appeared to produce ignitions most readily. The relative velocities of these rocks necessary to cause ignition of firedamp on collision was found to range from about 8 to 25 feet per second.

In experiments with hand picks against sandstone, ignitions were obtained with short, sharply delivered glancing strokes. This produced "stationary" sparking, that is, there was no shower of sparks through the explosive gas, but a localized yellow flash was observed at the moment of impact and over the area of contact of the pick point against the rock and a few red-hot particles moved slowly for a short distance at the surface of the rock as the face of the pick slid over it. If the blow produced a shower of sparks, firedamp did not ignite. Quartzitic sandstones were found to be most incendive in tests of this type, but some ignitions were obtained with sandstone of less uniform character classed as micaceous but containing quartzitic patches. Ignitions were obtained by the heated edge of a steel rod pressed against a rapidly revolving wheel of hard quartzitic sandstone. Tests with coal cutter picks set at the circumference of a rapidly revolving rock wheel, ignited firedamp by heating the rock surfaces.

In further tests ignitions were produced when the bits of chain or bar coal cutters made shallow cuts into quartz-bearing or siliceous sandstones, producing localized sparking in the form of red streaks or violent red flashes at the points of contact between the bits and the rock. No ignitions were obtained when similar cuts were made in pyrites or ironstone. In recent experiments on the effect of

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orientation between the impacting steel and sandstone rock surfaces, it was found that ignition probability is very low at normal impact, but increases steadily as the angle is reduced to about 15 degrees -- the smallest angle investigated.

For many years firedamp could not be ignited experimentally by contact of metals with pyritic rocks. However, several ignitions in coal mines were known to have occurred when picks cut into pyrite nodules. As a result, at one time instructions were issued that if iron pyrite nodules were encountered during cutting the machine was to be stopped and the nodule cut out by hand. Finally, a successful experiment was developed in which a rubbing action was applied to the pyrite rather than a cutting or a glancing blow. It was established that firedamp mixtures are easily ignited by rubbing blunt picks or pick boxes against pyrites. The rubbing action reduces some of the pyrite to a fine powder and heats it to between 200° and 300° C., at which temperatures the powdered pyrite oxidizes rapidly, ultimately giving a flame of burning sulfur that ignites the firedamp. The tests showed that worn picks are more dangerous than new picks. Cutters with worn picks require more power with greater release of heat; they produce more fine coal dust, which induces the release of more gas. If a machine encounters hard rock strata the picks can be worn in a few minutes.

The experiments showed that from the standpoint of ignition hazard owing to contact between metal and rocks, it makes little difference whether the picks are made of steel or tungsten steel or whether they are tipped with sintered tungsten carbide or made of bronze or special nickel-chromium steel. The character of the rock is the most important factor.

Experiments showed that ignitions of firedamp during under-cutting could be prevented by introducing enough carbon dioxide into the cut to insure a CO_2 concentration of about 25 percent in the atmosphere around the jib of the coal cutter.

Friction between iron or steel surfaces was found to ignite firedamp only with great difficulty, even when it produced a shower of sparks. If the sparks are concentrated by a wooden or metal shield, ignition occurs more readily. At speeds of contact of about 30 feet per second or more between the metal surfaces, ignitions resulted when the friction was great enough to raise the temperature of the steel to a white heat. Experiments in which a mild steel bar was cut by a hard steel wheel at a peripheral speed of 500 feet per minute showed that the probability of ignition of methane increased almost linearly with the oxygen content of the gas mixture. As the carbon content and hardness of the steel bar was increased, ignition became easier, and less enrichment of the air with oxygen was necessary to produce ignition. Ignition also became easier as the speed of cutting wheel increased. Friction between some metal surfaces, as in machine bearings, is dangerous for other reasons. It can heat coal or other combustible dusts to a glow or smoldering temperature, which in turn can result in a fire or possibly an explosion.

In recent years much work has been done on the ignition hazard from friction and impact between light alloys and steel. Under certain conditions an exothermic reaction of the thermit type results when rusty steel painted with aluminum is struck with a piece of steel. In practice most commercial paints contain a bonding medium, which when new interposes a barrier between the reacting surfaces and lessens the hazard. Preheating was found to deteriorate the paint film and increase the potential hazard. It was suggested that a similar deteriorating effect might result from normal aging of the paint. Experiments on the effect of aluminum smears on steel friction props have shown that much higher impact energies are

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needed to ignite firedamp if the aluminum is smeared on a clean steel surface than if it is smeared on a rusty surface. Red lead or iron oxide mixed with aluminum paint increased the violence of sparking. However, use of these materials in a primer coat reduced the hazard. Zinc coating on steel appears to be safer than aluminum, owing to its lower melting point and lower affinity for oxygen.

A series of experiments were undertaken following an ignition of firedamp in a coal mine in which 10 men were burned, 1 fatally, when a drilling machine encased in a magnesium alloy fell and struck a steel girder. The investigation disclosed that highly incendive sparks are produced by frictional impact of magnesium alloys on steel. The highest ignition probability occurred when the alloy struck the steel plate an angle of about 50 degrees. Ignitions resulted in some cases when the 36-pound test piece fell from a height of only 1.5 feet before striking the steel plate.

In a later study the incendivity of sparks produced by the impact of various cast light alloys against steel was investigated. It was found that: (a) The gas mixture is ignited by combustion of eroded metal particles which burn to form a flash; (b) the size, intensity, and incendivity of the flash decreases with decrease in the magnesium content of the alloy (there is an appreciable hazard even with pure aluminum); (c) the mixture most easily ignited contains 6.4 percent CH_4; (d) the angle of impact is not critical, ranging from 35 to 55 degrees, and outside of these limits the ignition probability is reduced and the chance of ignition appears to be small for normal impact or sliding friction; (e) the surface condition of the steel target plate has a great influence on the incendivity of the sparks, possibly owing to differences in roughness of the surfaces.

Interesting research is being conducted at present in England by Bowden on the ignition of methane-air mixtures by electrically heated, hot metal particles. It has been found that very small particles (less than 1 microgram for aluminum and magnesium) heated to their ignition point are effective in igniting gas. The minimum size of particle depends on the composition of the gas. A methane-air mixture containing about 7 percent methane was the most readily ignited, as compared with a mixture containing 9.5 to 10 percent methane, which was most readily ignited by a small aerated flame.

The order of effectiveness of the different metals tested(aluminum, magnesium, titanium, zirconium, pyrophor, cerium, and thorium) is the same as their heats of combustion, and the required size of particles increases as the heat of combustion decreases. These results indicate that the important factor under these conditions is the amount of heat liberated by the burning particles.

Another phase of the investigation concerns ignition of methane-air mixtures by sliding friction such as exists between a rotating steel wheel and a stationary piece of metal. Under these conditions the ignition probability increases with the rubbing speed and with the pressure or load of the stationary metal against the wheel. The order of effectiveness of the metals does not depend only on their heat of combustion. The important factor is thought to be the size and character of the particles that are abraded from the rubbing surfaces and projected into the gas mixture. With effective metals such as zirconium and pyrophor, the detached metal particles were very small (50 to 100 micrograms). The titanium particles were quite small (2 to 10 micrograms), but no ignitions were obtained as these particles did not burn on leaving the surface. Aluminum, magnesium, and their alloys produced no visible sparks or gas ignitions; the rubbing metal was plastically deformed and smeared over the sliding surfaces. In this ignition process the flying particles

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and not the rubbing surface govern the ignition, making the brittleness and mechanical properties of the metal very important. Normal impact between many pairs of metals, with high impact pressure, has produced no ignition of methane-air mixtures, although sparks have been observed with certain materials. This is thought to be due to the fact that local temperatures under such conditions are not very high and small metallic fragments are not detached too readily.

In a recent investigation conducted in two seams of a British coal mine, firedamp was diluted in the cut with compressed air and water sprays during overcutting. The experiment was made in dry and dusty seams. Two sets of sprays were used, one to spray the ingoing chain and the other to spray the outgoing chain. One spray attached to the cutter turret had 5 jets, 4 of which sprayed the machine turret, cutter chain, and roof and the end jet sent a powerful stream of water into the back of the overcut. A compressed-air line was incorporated in this spray so that compressed air was injected with the water, producing a heavy mist. The compressed-air pressure varied between 50 and 60 p.s.i.; the water pressure was 100 pounds.

During normal wet cutting operations in these tests the methane content ranged from 2.5 to 3.5 percent in one seam, and from 1.2 to 1.8 percent in the other. When the compressed air-water sprays were stopped, the methane content rose rapidly to the explosive range and beyond it; in some cases readings of up to 75 and 40 percent methane, respectively, were noted in the cuts of the two seams. According to reports from different collieries, similar percentages of methane have been encountered in cuts in other seams. The sprays are reported to fulfill the following important functions, which reduce the ignition hazard: (1) The methane content in the cut is reduced below the explosive range; (2) cuttings are thoroughly wetted, suppressing coal dust and reducing the explosion hazard; and (3) the cooling effect of the jets reduces the temperature of frictional sparks that may be produced during cutting. The tests indicate that after an extended period of idleness the sprays should be used to remove firedamp from the cut before the machine is put into action. During short periods of inactivity, even if it is necessary to stop the water sprays, a large volume of compressed air should be directed into the cut to prevent accumulation of firedamp which might be emitted suddenly.

FACTORS AFFECTING IGNITION HAZARD

The hazard of gas ignition by friction and impact depends on the nature of the contacting materials, the composition of the explosive gas, the available energy, and the type of contact. Research indicates that ignitions are produced most easily by friction between certain types of rocks. However, most mine explosions initiated by friction have resulted from contact between rocks and metals, as during undercutting of coal seams. Metal-to-metal contacts generally produce less incendive sparks than metal-to-rock contacts, but under some conditions, friction between light metal alloys and steel produces highly incendive sparks.

In all types of frictional heating the ignition probability depends on the rate of energy release, which is determined by the mass and speed of the contacting objects and the frequency of contact, the concentration of heat near the point of contact, the orientation of the surface at the time of contact, and the methane and oxygen content of the atmosphere. Weak mixtures of methane below the stoichiometric limit are more readily ignited by friction than rich mixtures, and turbulence appears to increase the ease of ignition. In contact between metals and rocks, frictional impact at small angles produced the most incendive heating; in contact between light alloys and steel, angles of 35 to 55 degrees were most hazardous; and in some metal-metal contacts sliding friction was worst. Normal or direct impact rarely produced firedamp ignitions.

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Of the rocks encountered in coal mines, siliceous or quartz-bearing sandstones present the greatest frictional ignition hazard; they are closely followed by iron pyrites. Some micaceous sandstones also have been found to constitute a hazard. Shales are considered less dangerous than sandstone, but some bituminous sandstones, which look like shales, can produce incendive sparks. It has been found that rocks with less than 35 percent quartz can give dangerous sparks. There is some indication that the moisture content of rocks may affect their incendivity.

In contact between rocks and metals the nature of the rock is far more important than that of the metal. Although little if any difference was observed between various steels in contact with rocks, in high-speed machine operations the surface hardness of the metal might have an effect. Sharp glancing blows proved most effective in producing ignitions by friction between steel and sandstone. In contact between steel and pyrite, the most hazardous conditions occurred during rubbing or sliding friction, which produces fine dust. In tests with cutters, the sharpness of the bits was found to be an important factor. Blunt bits are more hazardous than sharp bits because they produce more fine coal dust and upon encountering pyrite may produce and ignite pyrite dust. Another important factor in cutting or drilling is overloading machines; this can produce much heat and bring about conditions that lead to ignition.

In metal-to-metal contact the properties of the more readily oxidizable metal normally determine the degree of ignition hazard. The hardness, melting point, ignition temperature, specific heat, heat conductivity, and brittleness of the metals all play a role, in that they determine the size, duration, temperature, and heat capacity of the incendive sparks. Increase in the carbon and silicon contents of steels and rust on the steel surfaces promote the formation of incendive sparks during friction. Painting the steel surface, as with zinc coating, reduces the incendivity. Painting with aluminum may increase the ignition hazard, particularly on rusty steel.

During friction between light alloys and steel, the ignition hazard increases with the magnesium content of the alloy. Contact between aluminum and steel, particularly rusty steel, also gives incendive sparks under some conditions. The incendivity of metals seems to be related to their reactivity, as indicated by their position in the electropositive series of metals. In British coal mines the use of light metal alloys is being restricted or entirely discontinued.

MECHANISM OF FRICTIONAL IGNITION

As has been indicated, broadly speaking the ignition of gas by friction can be initiated either by heating near the points of contact or by heat transfer to the gas from the hot abraded fragments (frictional sparks). Despite extensive research there is no general agreement on the exact mechanism of the ignition process. This is due in part to the complexity of the problem and in part to the fact that the mechanism varies according to the circumstances.

Consider first frictional ignition by metal-to-rock contacts. In friction between steel and pyrite, the process requires production of fine pyrite dust and heating to a point where autooxidation starts; as this proceeds and the iron sulfide is converted to iron oxide, the temperature of the dust particles rises until a flame of burning sulfur appears and ignites the gas. A similar mechanism of ignition probably exists when excessive friction during cutting or drilling in a coal seam produces and heats very fine coal dust whose smoldering and eventual ignition can initiate a firedamp explosion. This has reportedly occurred in at least one mine. Frictional ignitions resulting from contact between steel and

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siliceous sandstone are more difficult to explain. It is agreed that they are due to heating at the surface of the rock and not to frictional sparks. According to some observations in Germany, the small abraded particles of steel adhere to the sandstone at the points of contact (See p. 8); as these are heated by friction, they oxidize and eventually ignite, initiating the gas explosion. If this is so, the nature of the steel should play a role in determining the ease of ignition, yet, experiments in Germany and England failed to establish differences between steels, and in some tests even copper alloys were reported to give ignitions readily. English tests make no mention of metal particles adhering to the rock surfaces. The question therefore remains, what is the mechanism of ignition and why is quartz so much more effective in producing incendive sparks than other rocks. The belief that hardness and low heat conductivity of the quartz are the governing factors has not been substantiated. Tests with harder rocks, such as carborundum and corrundum (which is probably a poorer thermal conductor than quartz) produced considerable sparks in frictional contact with steel, but firedamp was not ignited. An explanation suggested by Wynn is that the incendivity of quartz may be connected with its piezoelectric properties, which cause electrical discharges when quartz crystals are broken.

Frictional heating between light alloys and rocks has received little attention so far. As these metals are highly reactive, it is possible that their composition and other properties rather than the nature of the rocks may govern the probability of ignition.

The mechanism of ignition during friction and impact between rocks has not been explained satisfactorily. It is known that ignition is initiated at or near the points of contact, apparently by the heated surfaces.

In friction between metal surfaces there are many considerations. Bowden has found that with so-called stationary sparks of heated metal particles in an explosive gas, the size of particles required to produce ignition is related to the heat of combustion of the metal. This is pertinent in certain types of friction, for example, worn bearings, where there is considerable heating but no shower of sparks. In the familiar frictional spark process a certain amount of energy must be expended in shearing off the small particles of metal that are the nuclei of the sparks. This energy is transformed into heat, which raises the temperature of the particles. If the sparks are composed of relatively inert material their temperature may not exceed their melting point. With metals that are reactive in air, the freshly exposed surface oxidizes at the elevated temperature, and this further increases the temperature until the particle is heated to incandescence and is capable of igniting the gas. Aside from the chemical reactivity and the heat of combustion, several properties of the contacting metals are important in this process; brittleness, hardness, heat conductivity, and specific heat. Sparks of zinc and steel, which do not burn very readily in air, fail to reach as high temperatures as particles of magnesium and aluminum, which have low ignition temperatures and oxidize rapidly in air. This helps to explain why in some types of friction of light alloys with steel highly incendive sparks are produced. The part played by rust on steel surfaces has not been studied yet.

In contact between dissimilar metals, the one that is more readily oxidized generally determines the incendivity of the sparks. The size of the particles composing the sparks is important. Small particles are usually more incendive because they oxidize rapidly and have higher temperatures. If the particles are too small they may not have enough heat capacity and may lose heat faster during motion.

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The mechanism of gas ignition by friction when an aluminum-coated steel surface is struck with a tool, is thought to be a thermit reaction in which aluminum and iron oxide react rapidly. However, recent experiments indicate that the reaction process may be only normal oxidation of the abraded aluminum particles in air, possibly aided somewhat by reaction between the aluminum and iron oxide.

PREVENTION OF GAS IGNITIONS BY FRICTION

Experience and research have demonstrated that friction and impact between machines and minerals can produce firedamp ignitions during many operations in coal mines. Although the presence of frictional sparks is a warning of potential danger, it should be remembered that hot spots on the contacting surfaces can cause ignitions without visual sparking. To avoid ignitions, gas accumulation and frictional heating or frictional sparks must be prevented. A list of measures proposed for this purpose is given below. Based largely on European experience and research, some of these measures cannot be applied practically to our mechanized mining conditions.

(1) No coal cutting, roof caving, or other operations conducive to the production of frictional sparking should be performed in the presence of detectable gas in the mine atmosphere near the face. A check for gas should be made before such work is started and at frequent intervals thereafter.

(2) Special attention should be given to proper roof-control measures designed to reduce the formation of incendive sparks by breaking of hard sandstone beds.

(3) In general, ventilation at face areas in gassy mines where machines are used should be greatly improved. To accomplish this, auxiliary ventilation should be provided where necessary.

(4) Special ventilating and dust-suppressing arrangements and firedamp detectors should be provided on mining machines.

(5) Gas should be removed from cuts with large volumes of air as rapidly as it forms to keep the methane content below the lower explosive limit. Uncontrolled ventilation with insufficient air can make conditions more hazardous by bringing a mixture that is initially too rich into the explosive range.

(6) A survey should be made to determine the rate of gas emission and the composition of the atmosphere at various locations in cuts before ventilation plans are made. Consideration should be given to the possible sudden increase of gas output.

(7) Water should be injected on both sides of cutter bars, or better still compressed air-water sprays, which direct a strong mist into cuts, should be installed on mining machines. Such air-water sprays are more effective than either air or water alone. The mist dilutes the methane as it issues into the cut near the cutter bits, it wets the cuttings, and cools any frictional sparks that might form. The sprays should be started some time before cutting commences.

(8) Inert gas (carbon dioxide or nitrogen) should be introduced into cuts to render the atmosphere around the cutter bars nonexplosive. This last is an early recommendation that has not been put into practice. -- In large mining machines consideration might be given to the introduction of inhibitors into cuts.

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(9) Dry cutting and drilling should be avoided in gassy coal mines.

(10) Special care should be exercised in cutting seams adjoining siliceous rocks and those containing inclusions of iron pyrite. Similar care should be exercised in areas where faults or other gas feeders may be present.

(11) Whenever practicable, a cutting level or horizon should be selected that is free of any meterial that might produce sparks.

(12) Where practicable, several inches of coal should be left at the roof and on the floor to avoid cutting into adjoining hard rocks.

(13) To avoid excessive frictional heating mining machines should not be overloaded. When smoldering or other signs of heating are observed, the machine should be stopped.

(14) Unnecessary stopping should be avoided once cutting or drilling has begun, as this permits gas to accumulate in the cuts. During short periods of idleness, compressed air should be directed into cuts to prevent gas accumulation.

(15) The speed of cutting tools should be reduced.

(16) Mining machines should be operated in such a way as to limit the production of fine coal dust.

(17) Continuous mining machines, which make narrow cuts, should not advance too deeply into the seam unless there is provision for rapidly and adequately diluting and removing any gas that occurs.

(18) Use of high-silicon steel should be avoided, and rust on surfaces of steel roof supports and other structures prevented. The latter can be accomplished by using galvanized steel, or by applying zinc metal sprays or zinc chromate coating.

(19) Aluminum paints should not be used on steel surfaces in coal mines.

(20) Use of magnesium-base alloys should be limited or prohibited entirely. Care should be exercised to avoid friction and impact of all light metal alloys with steel and with hard rocks.

(21) Workmen should be warned of the potential hazards of frictional sparks, and they should avoid rapid, repeated blows with picks or tools at the same spot on rocks or metals.

(22) Attention should be given to frictional heating and sparking when using very hard bits and drills in high-speed mining machines.

(23) Fire-extinguishing facilities at mechanized coal faces should be improved. Water hose, with an ample supply of water, or other effective fire extinguishers should be provided.

The most important of the above recommendations probably relate to the provision of adequate ventilation at the coal face; the use of enough air and water in cuts; frequent checking for gas in the atmosphere; design and use of mining machines so as to facilitate rapid removal of gas; avoidance of overheating of

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cutting and other machines; and avoidance, insofar as possible, of hard rocks during cutting and drilling.

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